Global distribution of soil phosphorus retention potential

ISRIC World Soil Information

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Preface

ISRIC - World Soil Information has the mandate to create and increase the awareness and understanding of the role of soils in major global issues. As an international institution, we inform a wide audience about the multiple roles of soils in our daily lives; this requires scientific analysis of sound soil information.

Phosphorus is an essential element for life. Unlike carbon, oxygen, nitrogen, and hydrogen, it does not cycle between plants/soils and the atmosphere. It is mined, processed, and applied to the soil as fertilizer; it cycles between plants and soils and some of it is lost as runoff into lakes, streams and, ultimately, the ocean. Phosphate mines may be exhausted in the near future. In this context, ISRIC has initiated research to understand better the availability and dynamics of soil phosphorus.

The purpose of this study is to derive a world map of soil phosphorus retention potential in support of a model-based assessment of resource scarcity in relation to food security. The resulting GIS data are used to present a first approximation of possible recovery of P fertilizers added to soil, for application in model analyses at a broad scale. The study has been carried out in the framework of a quantitative modelling analysis initiated by Plant Research International, of Wageningen University and Research Centre, to study input requirements for enhancing agricultural productivity on the African continent, funded by the Netherlands Ministry of Economic Affairs, Agriculture, and Innovation (BO-10-011-007).

Prem Bindraban
Director ISRIC - World Soil Information

Summary

Limited availability of P in soils to crops may be due to deficiency and/or severe P retention. Earlier studies that drew on large soil profile databases have indicated that it is not (yet) feasible to present meaningful values for 'plant-available' soil P, obtained according to comparable analytical methods, that may be linked to soil geographical databases derived from 1:5 million scale FAO Digital Soil Map of the World, such as the 5 x 5 arc-minute version of the ISRIC-WISE database. Therefore, an alternative solution for studying possible crop responses to fertilizer-P applied to soils, at a broad scale, was sought. The approach described in this report considers the inherent capacity of soils to retain phosphorus (P retention), in various forms. Main controlling factors of P retention processes, at the broad scale under consideration, are considered to be pH, soil mineralogy, and clay content. First, derived values for these properties were used to rate the inferred capacity for P retention of the component soil units of each map unit (or grid cell) using four classes (i.e., Low, Moderate, High, and Very High). Subsequently, the overall soil phosphorus retention potential was assessed for each mapping unit, taking into account the P ratings and relative proportion of each component soil unit. Each P retention class has been assigned to a likely fertilizer P recovery fraction, derived from the literature, thereby permitting spatially more detailed, integrated model-based studies of environmental sustainability and agricultural production at the global and continental level (<1:5 million). Nonetheless, uncertainties remain high; the present analysis provides an approximation of world soil phosphorus retention potential.

Keywords: ISRIC-WISE data set, soil phosphorus retention, soil phosphorus deficiency, food security, uncertainty, extrapolation

1 Introduction

Soil fertility degradation has been coined as the single most important threat to food security in Sub-Saharan Africa (Stoorvogel *et al.*, 1993; Buresh *et al.*, 1997a; Gichuru *et al.*, 2003). A large portion of the soils has a low inherent fertility (FAO, 1993), but the major cause of soil fertility degradation in the region is the negative nutrient balance (e.g., nutrient output not replaced by inputs), notably soil nitrogen (N) and phosphorus (P) (Lindsay and Vlek, 1977; Smaling, 1998; Bundy *et al.*, 2005; Bindraban *et al.*, 2008). Continued application of more fertilizer-P than the crops utilize will increase the fertility of the soil, but, depending on soil characteristics and management practices, a large portion of the added P may be sorbed and thereby rendered unavailable to crops in the short term. Alternatively, in regions where inputs of P in fertilizer and manure to agricultural systems have exceeded output in harvested crops for several years, P loadings may exceed the natural capacity of soils to retain P leading to runoff and water quality problems such as eutrophication (Bouwman *et al.*, 2009; Harrison *et al.*, 2010).

Overall, the productivity and eco-efficiency of agricultural systems should increase to meet future global demands. However, 'quantitative information is lacking on where and what should be done (crop management, watershed management, socio-economic infrastructure) to realize such systems'[1], see also Keating *et al.* (2010). One of the soil properties for which little information is available globally is soil phosphorus, an essential and often limiting plant nutrient (Wang *et al.*, 2010). According to Vitousek *et al.* (2010), mechanisms that drive P limitation, and their interactions with the N cycle, have received less attention than mechanisms causing N limitation. Relatively few studies have considered interactive effects of soil N, P and potassium (K) (e.g., Janssen *et al.*, 1990; Perring *et al.*, 2008; Song *et al.*, 2010).

Modern agriculture is dependent on phosphorus derived from phosphate rock, which is a non-renewable resource. Current global reserves may be depleted in 50-100 years (Stewart *et al.*, 2005; Cordell *et al.*, 2009), but longer periods have also been reported (see Smit *et al.*, 2009). Phosphorus is needed by plants to form vital compounds and to store and transfer energy for growth (e.g., Sims and Sharpley, 2005). However, soil minerals and organic compounds can react quickly with water-soluble phosphorus applied with fertilizers to form soil compounds with very low solubility. Soil composition and agro-edaphic conditions largely determine the amount of phosphorus that may become available to plants. Knowledge of the geographic distribution and degree of soil P retention worldwide is useful, for example to support studies of food security. Information on soil P retention potential alone, however, may not suffice for this (e.g., Sanchez, 1976; Tan, 1992; Buresh *et al.*, 1997b; Fairhurst *et al.*, 1999). Probert (1983) defines sorption as the phenomenon whereby the concentration of phosphate in solution decreases when phosphate solutions come into contact with soil. As discussed by Wild (1950), phosphate sorption or phosphate retention are used synonymously; they are taken to 'mean the removal of phosphate from solution by soil or by a soil constituent - no particular mechanism is implied'. From an agronomic perspective, P retention is most important in the topsoil where P fertilizers are applied.

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[1] BO-10-011-007 *Resource scarcity and distribution in a changing world.*

As reviewed in a preceding study (Batjes, 2010), the amounts, forms (organic and inorganic), and distribution of P in the soil vary with different processes: natural processes that determine soil mineralogy and P sorption characteristics, as well as human-controlled processes such as the application and timing of P containing fertilizers, lime and organic material. Under natural conditions, the weathering and dissolution of rocks and relatively insoluble P containing minerals is a slow process. This weathering is only capable of supporting slow-growing vegetation and crops adapted to low P availability. In acid soils, various forms of iron (Fe), aluminum (Al) and manganese (Mn) oxides strongly bind P, while in calcareous soils P is mainly found in the form of Ca-compounds of varying solubility (Dabin, 1980; Schachtschabel *et al.*, 1998; Fairhurst *et al.*, 1999; Ryan and Rashid, 2006); volcanic soils rich in allophane strongly retain phosphorus (Andriesse *et al.*, 1976; Tan, 1992; Deckers *et al.*, 1998). Clay mineralogy and clay content directly affect P retention (Wild, 1950; Sanchez, 1976). Ultimately, the form of P in the soil will influence P availability to the plant. Actual uptake will be determined by soil water conditions, temperature, crop type and growth rate, root morphology and plant-specific characteristics to extract soil-P through excretion of exudates (Hoffland *et al.*, 1992). Mycorrhizal fungi may also be important in this respect (Smith *et al.*, 2003; Hoffland *et al.*, 2004; Li *et al.*, 2006). As the underlying processes are manifold and complex, they remain cumbersome to model irrespective of scale (e.g, Wolf *et al.*, 1987; Daroub *et al.*, 2003; Dzotsi *et al.*, 2010; Ohno and Amirbahman, 2010; Wang *et al.*, 2010).

Different crop types will respond in different ways to identical rates of P fertilizer, for given conditions of climate, soil and land management. Chemical soil tests, such as P-Olsen and P-Bray, can provide an accurate relative index of the amount of P that a given crop may utilize from a soil, but rarely, if ever, can they provide an absolute measure of it (Thomas and Peaslee, 1973; Landon, 1991). Earlier studies that drew on two large soil profile databases (Batjes, 2010, 2011) have indicated that it is not (yet) feasible to present meaningful values for 'plant-available' soil P that may be linked to soil geographical databases that consider the Legend of the Soil Map of the World (e.g., FAO-Unesco, 1974; FAO, 1995a; Batjes, 2006). Therefore, an alternative solution for studying possible responses to soil fertilizer-P applied to soils, at a broad scale, was sought. The approach described in this report considers the inherent capacity of soils to retain phosphorus (P retention), in various forms. The inferred capacity for P retention of each FAO soil unit is rated into four broad classes, rated from low to very high P retention. Each of these classes is then assigned to a likely fertilizer-P recovery fraction, derived from the literature, thereby permitting spatially more detailed, integrated model-based studies of environmental sustainability and agricultural production than have been possible so far (e.g., Conijn *et al.*, 2011a; Conijn *et al.*, 2011b). The pronounced effect of P sorption in strongly weathered tropical soils means that the difference between optimal and economic rates of P fertilizer application will be much greater in the tropics than in temperate regions (Tiessen, 2005).

2 Processes and factors that affect soil P retention

2.1 Processes

Phosphorus in the soil is only partly soluble and not very mobile. Overall, exchange reactions involving adsorbed-P are very slow compared to that of other nutrients. Soil phosphorus tests provide important information for estimating the P nutrient status of the soil. Generally, plants can only utilise a small fraction of the total P in soil, corresponding with the so-called 'available-P.' This amount is related to the so-called labile soil P, sometimes referred to as the 'intensity' of the nutrient in the profile. In practice, however, it is difficult to partition the different soil-P reactions. As described by Ryan and Rashid (2006), the process is a 'continuous one - rapid at first, but continuing slowly to a more stable hypothetical equilibrium state whereby metastable compounds revert to more stable ones.'

Dynamic processes in soil include P dissolution, precipitation, adsorption and desorption; biological processes involve mainly immobilization within the plant roots and bacterial biomass and subsequent mineralization (e.g., Fixen and Grove, 1990; Bundy *et al.*, 2005; Sims and Sharpley, 2005; Ryan and Rashid, 2006). Strongly bonding anions such as phosphate show typical adsorption-desorption hysteresis in soil (McBride, 1994). In flooded soils, the availability of P to crops is further affected by changes in redox potential (Lindsay and Vlek, 1977). Whereas sparingly available or non-available P is not accessible to roots on the time scale of one or more crop cycles, a small fraction of this pool may gradually become available during long-term soil transformations (Wolf *et al.*, 1987; Gassner and Schnug, 2006). Mineralization of soil organic matter and crop residues by soil microorganisms forms an important source of plant-available P in many strongly weathered and coarse textured soils, provided levels of organic matter are elevated. Retention of phosphate by non-living organic matter in soil, however, is usually believed to be small (Wild, 1950); it is possibly due to a reaction of the phosphate with Fe^{3+}, Al^{3+} and Ca^{2+} ions which are associated with the organic matter. According to Daly (2001), organic matter may inhibit P sorption from solution to soil, while Afif *et al.* (1995) reported that organic matter delays but not does prevent phosphate sorption by Cerrado soils from Brazil.

Possible transformation of phosphorus in soils are schematized in Figure 1; the division among the inorganic solid phases is somewhat arbitrary, given the heterogeneity of soil components and diversity of processes involved (Fixen and Grove, 1990). An in depth discussion of these processes is beyond the scope of this study (e.g., Bolt and Bruggenwert, 1978; Tan, 1992; McBride, 1994).

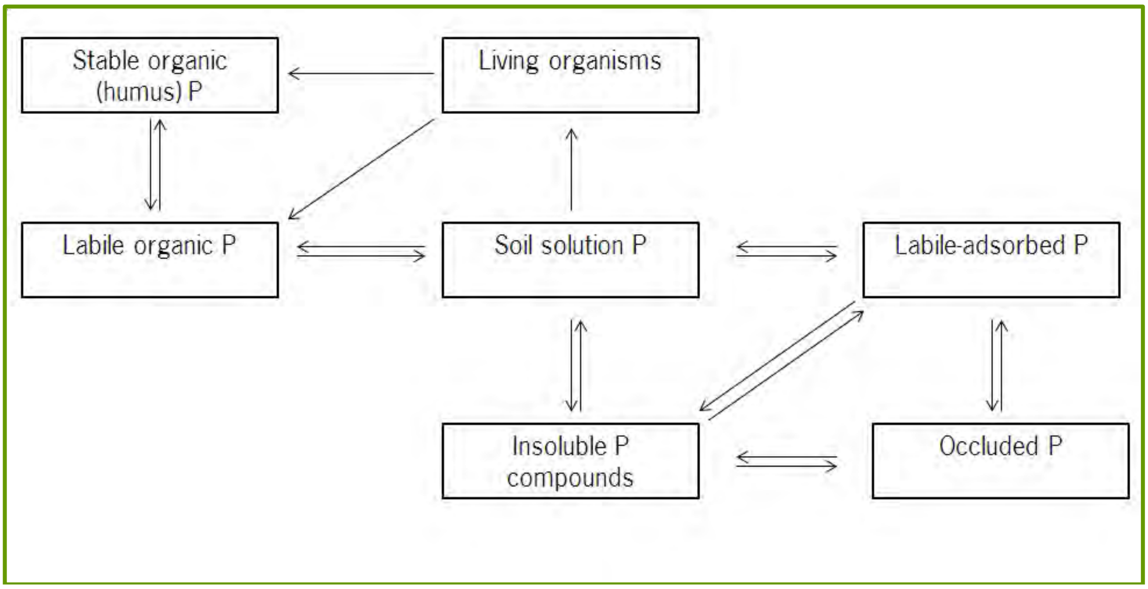


Figure 1
Schematic representation of possible processes of P transformation in soil (After: Fixen and Grove, 1990).

The removal of P from soil solution subsequent to fertilizer P addition may be seen as a continuum of processes, from adsorption to precipitation, that results in a continuum of chemical states (i.e., adsorbed, chemisorbed, amorphous-crystalline-occluded, precipitated) for the transformed P (Fixen and Grove, 1990). In practice, definition of various forms (pools) of P is dependent on the laboratory techniques used. Historically, there has been confusion between the terms P fixation and P retention. As discussed by Wild (1950), phosphate sorption or phosphate retention are often used synonymously. They are taken to 'mean the removal of phosphate anions from solution by soil or by a soil constituent'; alternatively, phosphate fixation is used to 'describe any change that the phosphate undergoes in contact with the soil, which reduces the amount that plant roots can absorb' (Wild, 1950). Tisdale *et al.* (1975), however, are of the opinion that P retention refers to that part of adsorbed P that can be extracted with dilute acids (i.e., P fraction relatively available to plants), while P fixation is reserved for the portion of soil P that is not extractable by dilute acids (i.e., not readily available to plants). Under certain conditions, the distinction between phosphorus fixation and retention is rather obscure (Tan, 1992) in a material as complex as soil.

It should be noted that P retained by soil is not necessarily 'fixed.' As such, 'fixation' has an erroneous connotation of irreversibility (Sanchez, 1976). If the phosphate retained by soil constituents could be released to the soil solution at a later date and a reasonable rate for plant uptake, then retention is considered advantageous rather than disadvantageous to fertility management (Pa Ho Hsu, 1977; Sanchez *et al.*, 1997b). Therefore, many investigations have discontinued use of the term 'phosphorus fixation.' In this study, the term P retention will be used as it does not imply any underlying processes (see Wild, 1950).

2.2 Factors

Phosphate retention is an inherent property of a soil and it does not change. It is a continuous (time dependent) process that occurs in all soils that gradually renders phosphate ions temporarily unavailable to plants. The underlying chemical processes are manifold and complex, as discussed earlier, and they remain cumbersome to model (e.g., Wolf *et al.*, 1987; Dzotsi *et al.*, 2010). Based on Section 2.1, three main factors will be considered in the present expert-based, global assessment of potential phosphorus retention by soils:

Soil mineralogy

Soil mineralogy has a great effect on P retention (e.g., Dixon *et al.*, 1977; Deckers *et al.*, 1998; Schachtschabel *et al.*, 1998). Volcanic soils tend to have the greatest P retention of all soils since they contain large amounts of amorphous material or allophane. In the FAO Legend, these correspond with Andosols. Overall, there is a tendency of highly siliceous members of Andosols to have less P retention (Andriesse *et al.*, 1976). After volcanic soils, strongly weathered Ferralsols and Acrisol units have the greatest P sorption capacities (Driessen and Dudal, 1989; Macias Vasquez, 2008). This is due to the presence of large amounts of aluminum and iron oxides and highly weathered kaolinitic (1:1) clay minerals; in addition to the content of iron and aluminum oxide, the degree of crystallisation is also important (Sanchez, 1976). Plinthite nodules have a great capacity to sorb P (Tiessen *et al.*, 1991). Fox *et al.* (1968) and Sanchez (1976) ranked the P retention capacity of the most common components of clays as follows: amorphous hydrated oxides > crystalline oxides (e.g., gibbsite, goethite) > kaolinite (1:1 clays) > montmorillonite (2:1 clays). Less acid soils with weathered layer silicate minerals have an intermediate P retention. Finally, at the other end of the spectrum, organic soils (Histosols), Podzols and coarse textured soils have low P sorption capacities. Alternatively, P retention may be moderate to high at depth in acid Podzols that have a relatively thick, spodic B horizon in which amorphous compounds, consisting of organic matter and aluminum, have accumulated (Väänänen, 2008; Väänänen *et al.*, 2008). Strongly acid, oxidized pyritic materials (Thionic Fluvisols) strongly bind phosphorus. P sorption in alkaline, calcareous soils is generally related to $CaCO_3$ content, but in some alkaline soils amorphous Al and Fe oxides can be the principal determining factors of P sorption (McBride, 1994; Bertrand *et al.*, 2003). Much of the required information on soil mineralogy is embedded in the FAO soil unit classification (FAO-Unesco, 1974); alternatively, it may be derived from the cation exchange capacity of the clay-size fraction (CEC_{clay}) as a proxy.

Clay content

P sorption capacity increases with clay content, because clay particles have a large surface area on which phosphate can be sorbed (phosphate is an anion, therefore soil particles that have an anion exchange capacity will from strong bonds with phosphate). Clayey materials with more than 20% iron or aluminum oxides in their clay-size particles sorb large quantities of added phosphorus, transforming them into slowly soluble iron and aluminum phosphates that are not immediately available to plants (Sanchez *et al.*, 2003). High P retaining soils are often clayey with red or yellowish colours indicative of high contents of iron and aluminum oxides; usually, such soils have a strong granular structure (e.g., Ferralsols). High phosphorus retention is related to high clay content, therefore most sandy red soils do not fall in this category (Sanchez *et al.*, 2003). Alternatively, most fine to medium textured soils have large capacities to hold phosphate by adsorption and precipitation. Invariably, subsoils sorb more phosphate that surface soils (Probert, 1983).

Soil pH

The relationship between the type (and amount) of clay minerals and soil pH is important, as it influences the mechanisms involved in the retention of phosphorus in different soil types. The forms of phosphate ions present depend on soil pH; $H_2PO_4^-$ ions will prevail under acidic conditions, while HPO_4^{2-} ions are dominant under alkaline conditions, and $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-} ions can co-exist at pH6.5 in the soil solution (Tan, 1992).

As schematised in Figure 2, there are various valleys of phosphorus retention in soil. Availability of phosphorus is primarily dependent upon the pH of the soil. However, soil pH as such does not affect phosphorus retention directly. Rather, it is a proxy that shows how certain minerals (i.e., iron, aluminum and calcium), interact with phosphorus in the soil, and it is this interaction that affects phosphorus availability and/or retention. At low pH (<5.5), soils have greater amounts of iron and aluminum in the soil solution, which can form very strong bonds with phosphate ions. Under such low pH conditions, variscite and strignite are likely regulating factors of inorganic P solubility (see Pierzynski *et al.*, 2005). Alternatively, in alkaline soils, phosphorus tends to be converted to calcium phosphate whereby availability to plants is reduced. Above pH 8.5, the presence of sodium may increase the availability of phosphate by formation of soluble sodium phosphate, but exchangeable Na-levels may become limiting for most crops (Landon, 1991). Soil pH also influences the solubility of different phosphate compounds in soils dominated by 2:1 clays, when clay content is high, as montmorillonite and other smectite minerals have a small anion exchange capacity (Borchardt, 1977). A soil pH in the range 6.0-7.5 will generally result in the greatest availability of fertilizer and soil P (Bundy *et al.*, 2005); other authors generally coin pH 6.0-7.0 (Wild, 1950; Landon, 1991). Nonetheless, it should be noted that some degree of P retention may occur even when the pH is between 6 and 7. This may be the case, for instance, for soils that have ferric or ferralic properties (FAO-Unesco, 1974), as occurring in Western Africa for example, or some soil units with a hue redder than 5YR in the Munsell colour scheme (Munsell, 1975). Similarly, on some Nitisols, added P fertilizer is not reflected well in higher available P values although plant growth responds favourably, pointing at marked P sorption (Hinga, 1977).

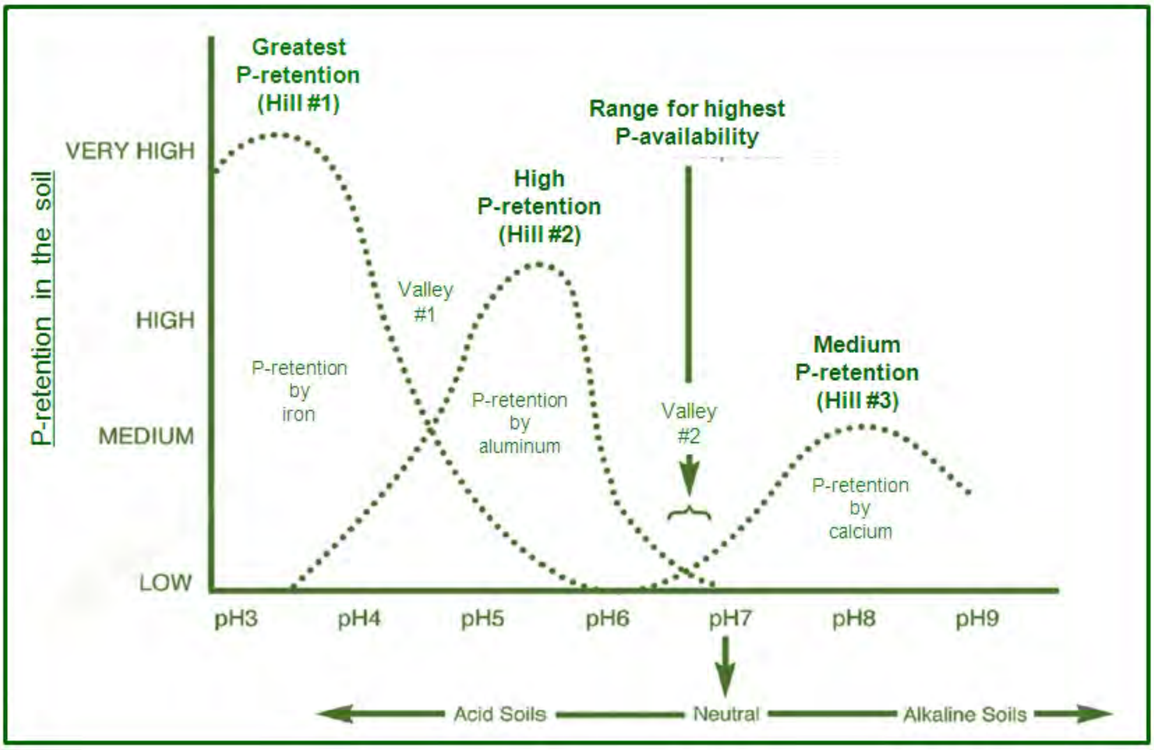


Figure 2
Phosphorus retention in soils (After: FIFA, 2006).

Climate (Temperature, Moisture)

Geographically, as rainfall, temperature and weathering increase the role of Ca in P adsorption reactions decreases and that of Al and Fe increases (Fixen and Grove, 1990). Soil temperature influences the rate of P fertilizer reactions with the soil, with reaction rates increasing with increasing soil temperature and moisture (Bundy *et al.*, 2005). Phosphate ions uptake by plants occurs mainly from the soil solution, therefore phosphorus uptake is greatly reduced in dry soils. Wet or cold conditions that reduce root metabolic activity will also slow phosphorus uptake. Dry and cold regions were specifically excluded from the phosphorus retention potential map produced by USDA (Reich, 1998). However, there is no evidence that the total amount of phosphate that can be retained by a given soil type will change with temperature (Wild, 1950). Therefore, climate has not been considered as a regulating factor in the present study. Any climatic constraints for crop production will later be filtered out automatically by the crop models.

3 Data and methods

3.1 Soil geographic and attribute data

Soil geographical and attribute data for this study were taken from the 5 by 5 arc-minutes version of the ISRIC-WISE database of derived soil properties (Batjes, 2006). The underpinning soil geographical data were taken from the 1:5 M scale Digital Soil Map of the World (FAO, 1995b). Estimates for derived soil properties for each FAO soil unit (for 5 depth layers of 0.2 m, down to 1 m depth or less for shallower soils) were based on analyses of the ISRIC-WISE profile database (see Batjes *et al.*, 2007).

3.2 Methods

The broad rules in Section 2 about the combined effect of soil pH, clay content and soil mineralogy on potential P retention by the soil were translated to automated decision rules. Derived soil properties for 0-100 cm were averaged to rate potential P retention by soil unit in four broad classes. Various possible class intervals for soil pH have been tested and results visually checked using the preliminary GIS output. Ultimately, the following pH intervals were considered for this study: ≤5.0, 5.0-5.5, 5.5-6.0, 6.0-7.0, 7.0-8.5, and >8.5. Within each of these classes, the possible effects of soil mineralogy and clay content on P retention were considered next.

CEC_{clay}, the cation exchange capacity (CEC) of the clay fraction corrected for the contribution of organic matter, provides a proxy for soil mineralogy. However, this criterion is most useful for strongly weathered soil units with CEC_{clay} <24 $cmol_c\ kg^{-1}$ (see Bennema, 1974; Klamt and Sombroek, 1988). CEC_{clay} ≤12 $cmol_c\ kg^{-1}$ has been used here for strongly weathered soil types as additional criterion for differentiating between soil units that may have a Very High respectively High inferred P retention potential. Uncertainties attached with the derivation of CEC_{clay} values for the diverse soils of the world, however, can be large; values for CEC_{orgC} may vary from 150 to 750 $cmol_c\ kg^{-1}$ with an average value of 350 $cmol_c\ kg^{-1}$ (see Klamt and Sombroek, 1988; Schachtschabel *et al.*, 1998; Batjes, 2002). CEC_{clay} alone, however, does suffice for the identification of Andosol (CEC_{clay} > ~80 $cmol_c\ kg^{-1}$) and Histosol units. Therefore, for some soil units, part of the necessary information on soil mineralogy (see 2.2) had to be derived from the FAO soil unit name; the corresponding soil units are flagged in Appendix II (see footnote b). Class ratings for these soil units were adapted in accordance with general pedological knowledge (see Probert, 1983; Deckers *et al.*, 1998; Driessen *et al.*, 2001; Soil Survey Staff, 2010).

Broad class limits for clay content were tested and results visually inspected using GIS. As a result of this evaluation, class limits were set at <15% clay and ≥ 35% clay, the former being considered indicative for weaker and the latter for stronger P binding properties in soil (within a given pH range and soil mineralogy class), with 15-35% taken as intermediate class. Accordingly, the class rating was decreased by one class when clay% <15 and increased by one class when clay% >35% (e.g., from Moderate to High).

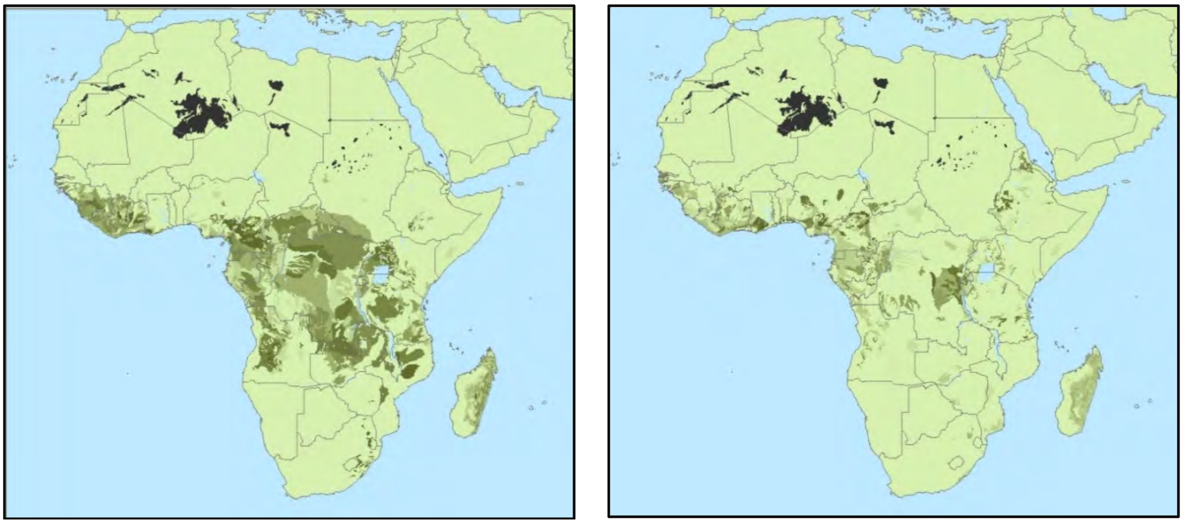
4 Results and discussion

4.1 Global distribution of soil phosphorus retention classes

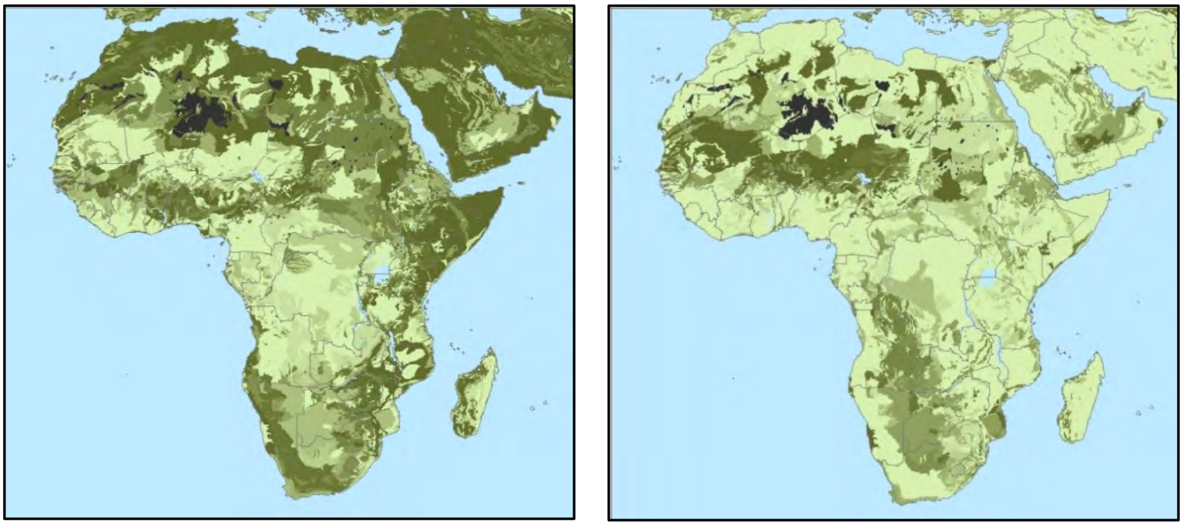
First, a map of P retention potential was made based on FAO soil classification unit only, using the information that is embedded in the definition of the soil unit. However, this type of approach proved to yield a rather coarse map upon visual inspection of the preliminary GIS output.

More detailed analyses were then made that explicitly consider differences in soil pH, clay content and inferred soil mineralogy of different FAO soil units, as well as the full map unit composition. Recommended class limits for soil pH, clay content and clay mineralogy were based on the overview in Section 3.2. Inherently, such class boundaries will be fuzzy, not crisp (Burrough, 1989). Similarly, derived values for CEC_{clay}, clay content and soil pH used to assign each soil unit to a given P retention class have large uncertainties attached to them (Batjes, 2006). For example, the class limit for pH may have been set at 5.0 while the derived pH value for a soil unit is given as 4.9 ± 0.4, or the class limit for clay content may be defined as >35% while the derived clay content is given as 36 ± 5%. Similarly, uncertainties are associated with the map units in terms of their geographic location as well as composition in terms of FAO (1974) soil units mapped and their relative extent (see Nachtergaele *et al.*, 2011). Finally, the soil geographical base is at a scale of 1:5 000 000; as such, it is meant to show broad soil patterns worldwide.

There are 4392 unique mapping units (SUIDs) for the world in the GIS database. Each map unit, as represented by a number of 5 by 5 arc-minutes grid cells, may consist of up to eight, different soil units. The P retention potential for each of these soil units was first rated in four classes using the criteria described in Section 3.2: very high (VH), high (Hi), moderate (Mo), and low (Lo). Subsequently, the relative proportion of the various classes within each mapping unit was determined; Africa is used as an example in Figure 3. When occurring, extensive areas (>50%) of Glaciers (GL), water bodies (WR) and rock outcrops (RK) have been mapped as miscellaneous units (MISC, see Appendix III).



(a) Very high *(b) High*



(c) Moderate *(d) Low*

Figure 3
Relative proportion of soil units with a very high, high, moderate and low inferred phosphorus retention potential in Africa (rock outcrops >50% are shown in black).

To facilitate comparison with results derived from other studies (Section 4.2), the number of legend classes has been reduced/condensed based on the cumulative proportion of Lo, Mo, Hi, and VH ratings that occur within each mapping unit. Four subclasses were used for this: 1) ≥ 75%, 2) 50-75%, 3) 25-50%, and 4) <25%; the most limiting P retention class is considered first in the clustering procedure. The first step lead to 280 (generalized) P retention potential classes like 'Mo1Hi4 with 80% of Mo and 20% of Hi-rated soil units' resp. 'Mo1Hi4 with 90% of Mo and 10% Hi-rated soil units'. The latter, in turn, consists of 29 different soil mapping units as illustrated in Appendix III.

Table 1

Example of procedure for clustering information on inferred P retention potential by mapping unit.

MainCLASS	FullCLASS	VH	Hi	Mo	Lo	MISC
Mo2	Mo2Lo2	0	0	50	50	0
Mo2	Mo2Lo3	0	0	55	45	0
Mo2	Mo2Lo3	0	0	60	40	0
Mo2	Mo2Lo3	0	0	65	35	0
Mo2	Mo2Lo3	0	0	66	34	0
Mo2	Mo2Lo3	0	0	67	33	0
Mo2	Mo2Lo3	0	0	70	30	0
Mo2	Mo2Lo3Hi4	0	5	70	25	0
Mo2	Mo2Lo3Hi4	0	10	50	40	0
Mo2	Mo2Lo3Hi4	0	10	60	30	0
Mo2	Mo2Lo3Hi4	0	20	50	30	0
Mo2	Mo2Lo3Hi4VH4	5	20	50	25	0
Mo2	Mo2Lo3VH4	5	0	50	45	0
Mo2	Mo2Lo3VH4	5	0	70	25	0
Mo2	Mo2Lo3VH4	10	0	50	40	0
Mo2	Mo2Lo3VH4	10	0	60	30	0
Mo2	Mo2Lo3VH4	20	0	50	30	0

Note: *MainClass* stands for the spatially dominant P retention class in a given map unit; if one or more P retention classes have the same relative extent, the most limiting class has been taken. The information on P retention for a given map unit *(FullClass)* has been condensed according to the proportion of low (Lo), moderate (Mo), high (Hi) and very high (V) of P retention classes that occur in the map unit, using four subclasses for the areal extent: 1) ≥ 75%, 2) 50-75%, 3) 25-50%, and 4) <25 %. MISC stands for miscellaneous units (e.g., Water (WR), Land Ice/Glaciers (GL), and Rock outcrops (RK)).

Further clustering, lead to 166 unique legend classes *(FullClass)* for the world, for example 'Hi2Lo3Mo4' or 'Hi2Mo3.' Finally, only the most extensive and most limiting P retention class *(MainCLASS)* has been shown on the generalised GIS map, resulting in a legend with 16 classes (e.g., VH1, Hi2, Me3, or RK1). Classes like 'VH3'', 'Hi3', 'Mo3' and 'Lo3' are typically comprised of a combination of several soil P retention classes, albeit in widely varying proportions.

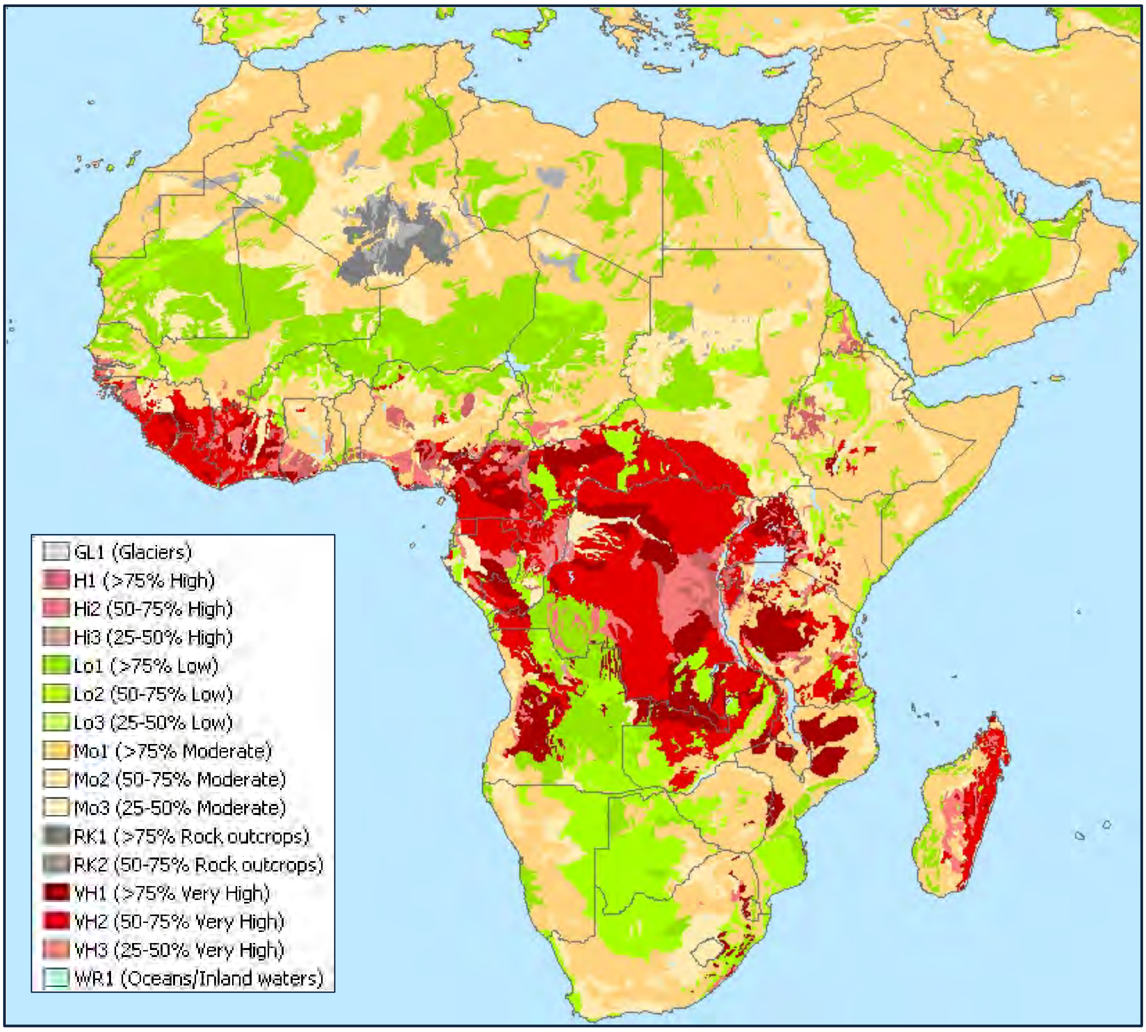


Figure 4

Generalized map of phosphorus retention potential of soils in Africa (Legend units are for the whole world, see text for coding conventions and Figure 3 for the underpinning information).

The final steps of the clustering procedure are illustrated in Table 1. The resulting, generalised map for Africa is presented in Figure 4, as an example. The global map is shown in Figure 5 and added as a GIS layer to the (on-line) report. Estimates for P retention potential by FAO soil unit, as listed in Appendix II, can be linked to the GIS layer using the unique map unit code *(SUID)*. The structure of the corresponding attribute table, *P_RetMap_FINAL*, is described in Appendix I. Modelling studies should take into account the full mapping unit composition.

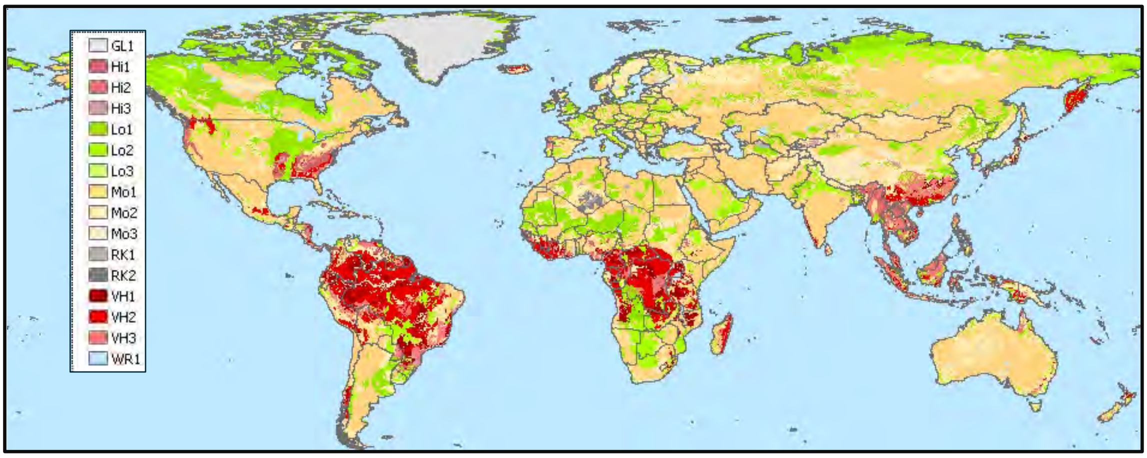


Figure 5
Generalized map of soil phosphorus retention potential (Map does not include Antarctica; see text for details).

4.2 Evaluation of the generalized P retention map

There are not many options for evaluating the results of the present study (Figure 5). Further, the use of qualitative class descriptions, such as 'high P-retaining' soil, complicates the comparison of different maps/studies.

The map of soil P retention potential produced by Reich (1998) considers the world soil map and soil climate map of USDA-NRCS (at 2 arc-minute resolution) and four qualitative P retention classes. Apparently, the mapping procedure only considered the dominant soil unit in a given map unit as the differentiating criterion. Nonetheless, for the tropics the broad distribution of potential P retention classes derived from this study (Figure 5) is similar to that presented by Reich (1998). Similarly, the map of 'high-P fixing' soils in Africa, prepared by ICRAF (see Sanchez *et al.*, 1997b, p. 14), corresponds well with the pattern of 'Hi' and 'VH' classes in Figure 4, keeping in mind any possible differences in qualitative class definitions. For Queensland, Australia, the general pattern corresponds to that described by Probert (1983), with areas of mainly Ferralsols showing the highest potential for phosphate retention and soils of the 'Brigalow lands' (mainly Vertisols, Luvisols, Solonetz, and Podzols) the lowest (intermediate to low P retention).

Large sections of East Africa are mapped as belonging to the moderate P retention class (Figure 3), except where Andosols, Ferralsols and some Acrisol subunits, with a very high P retention potential, are important (e.g., Kenya highlands, Uganda, Rwanda). According to Mokwuyne *et al.* (1986), many soils of East Africa could not be designated as high P retaining. Clayey soils with an 'iron oxide/clay ratio' >0.2 can adsorb large amounts of added-P, while sandy and loamy members of Acrisols and loamy Ferralsols generally do not (Sanchez and Logan, 1992). Regional differences in profile texture within a given FAO soil unit, however, cannot be considered in the present study. By their nature, small-scale world soil maps (e.g., 1:5 000 000) cannot show as much detail on the ground as larger-scale maps (e.g., 1:500 000) would (e.g., Soil Survey Staff, 1983; Landon, 1991). Hence the on-going update of the information on the world's soil resources, at an increasingly finer resolution, in the context of various international activities using various techniques (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009; Sanchez *et al.*, 2009; Nachtergaele *et al.*, 2011)

Strong P retention is most extensive in the humid tropics, sections of subhumid West and East Africa, the South American savannahs', and in many clayey red soils of the tropics, which is in accordance with general observations (Sanchez and Logan, 1992; van Wambeke, 1992; Reich, 1998; Nandwa, 2003). Alternatively, P retention is generally moderate in arid and semi-arid areas due to the presence of calcium carbonates and elevated clay content, whereas it is low in coarse textured and organic soils. From the soil science literature (Deckers *et al.*, 1998; Schachtschabel *et al.*, 1998; Driessen *et al.*, 2001), however, there is little evidence of large extents of soil units with a very high potential for P retention in cold temperate regions as delineated on the map by Reich (1998). In the absence of a detailed report for that mapping exercise, however, the reasons for the observed differences in interpretations cannot be assessed here.

4.3 Possible fertilizer P recovery

The recovery of fertilizer phosphorus applied to a given soil, defined as the ratio of P applied to P taken up, will vary with crop type, management practices, and weather conditions. Nitisols in Kenya, for example, often show high P sorption (Hinga, 1977), but this need not result in acute P deficiencies (Wielemaker, 1984; Deckers *et al.*, 1998). Recovery (utilization) of fertilizer-applied phosphorus by plants is usually less than 30 per cent in the first year; the long-term recovery is usually higher (e.g., Wolf *et al.*, 1987; Buresh *et al.*, 1997b; Sanchez *et al.*, 1997b). Overall, the greater a soil's capacity for phosphate retention, the greater amounts of fertilizer-P will be required to overcome a possible phosphate deficiency and/or maintain soil phosphate levels. Judicious liming will facilitate P-uptake in strongly weathered soils such as Ferralsols (e.g., Sanchez, 1976; van Wambeke, 1984). Alternatively, lowering of the soil pH would seem the obvious solution for calcareous soils, but the cost of the amount of acid (sulphur) needed to neutralize such soils is often prohibitive (e.g., FIFA, 2006). Application of organic matter as soil amendments on calcareous soils can increase the efficiency of applied P fertilizers (Delgado *et al.*, 2002).

Various values for fertilizer-P recovery fractions have been reported worldwide for crops. An average 29% of P added with fertilizer and manure is removed by harvested crops in the United States, ranging from <1% in Hawaii, with a predominance of high P-retaining volcanic soils, to 71% in Wyoming with vast extents of Xerosols, Regosols and Kastanozems (see Kamprath, 2000). According to Smil (2000), single-year-response recovery of fertilizer P often ranges from 15 to 25%, while longer-term recovery in cropping systems is more typically 50 to 60%. Heineman (1996, cited in Sanchez *et al.*, 1997b), reported that 68% of a 150 kg P ha^{-1} application of diammonium phosphate was recovered by a maize-bean rotation over 5 years in a Ferralsol of western Kenya. Within the pH 6-7 range where phosphorus availability is generally at its highest and retention due to iron, aluminum, and calcium is at its lowest, and in the very best of circumstances, crops may use 15% of the broadcast-applied phosphorus fertilizer and 30% of the band-applied phosphorus fertilizer, based on the results of several US laboratories (AgSource, 2006). Alternatively, when the soil is strongly acidic or alkaline, these recovery fractions could drop to 5% for broadcast and 15% for banded P-fertilizer application (AgSource, 2006). Methods of P fertilizer application will also determine phosphorus use efficiency (FIFA, 2006).

The rate of fertilizer P necessary to overcome P deficiency increases with increasing P sorption capacity of the soil. The duration of residual effects of fertilizer P application will vary according to soil type, crop type and land use/management history. Residual effects on low P-sorbing soils are shorter than on high P-sorbing soils, except for volcanic soils (van Wambeke, 1984; Buresh et al., 1997b; Sanchez et al., 1997b). The greater the number of crops harvested per year, the shorter the residual effect will be. Residual effects of large applications of P on the high P-sorbing soils of the Cerrado region, Brazil, can last for 5 to 10 years (see Sanchez et al., 1997b). Freshly precipitated iron and aluminum phosphates form good sources of P for plants provided these materials occur in close proximity to growing roots; with aging, these precipitates will become less available to crops following recrystallization. Alternatively, on some calcareous soils of semi-arid regions much of the applied P is precipitated as insoluble calcium phosphates that remain largely unavailable to cereal crops (Diez et al., 1992; Frischke et al., 2004). The release of P from Ca-apatite is a straight solubility reaction, which is slow in soils with a high pH and Ca content (Tan, 1992; Sanchez et al., 1997b). Recovery fractions of fertilizer P in wheat grain on calcareous soils have been shown to decrease with incremental rate of fertilizer in New South Wales, Australia, pointing at high potential levels of fertilizer P-residues in this soil/ climatic environment (Holford and Doyle, 1993). Consequently, P-replenishment strategies in the subtropics and tropics are limited to soils with hydrous oxides of Fe and Al (Tan, 1992; Sanchez et al., 1997a).

According to Deckers et al. (1998), the high phosphorus retention capacity of generally fertile Andosols may be overcome by 'satisfying' the phosphate demand. However, upon P fixation allophane minerals can form new P-sorbing sites, which makes them an ultimate sink for P with very slow desorption rates (Sanchez et al., 1997b). Soils near young volcanos with volcanic admixtures, however, can be relatively fertile and high in available P (Wielemaker, 1984).

Summarizing, recovery rates of fertilizer applied phosphorus can vary widely depending on the plants grown (i.e., crops or pasture), weather, soil type, source/ type of phosphorus fertilizer, and application method/ timing; on most soil types part of the applied P will be(come) available to crops in the succeeding year(s) (see Sanchez et al., 1982; van Wambeke, 1992; Smil, 2000; FIFA, 2006). Further, most soil types do not possess an infinite capacity to retain P; for long-term environmental and agronomic sustainability, P-application through fertilizers and manure should not exceed P-removal.

In view of the above, a practical solution had to be found here for linking the present qualitative classes for soil P retention to plausible ranges for the P-recovery fraction for a 'default rainfed, cereal crop' (Table 2). Indicative values for the latter were taken from Driessen and Konijn (1992); inherently, there will be a gradient in the possible P-recovery fraction within each P retention potential class. Tentatively, indicative recovery fractions (during the year of fertilizer application) for each P retention class may be estimated as the mid-class value for the recovery fraction to facilitate crop modelling runs (i.e., 0.035 kg kg-1 for the Very High, 0.075 kg kg^{-1} for the High, 0.125 kg kg^{-1} for the Moderate, and 0.225 kg kg^{-1} for the Low P retention class). Alternatively, so-called windows-of-opportunity (e.g., Bouma et al., 1998) may be simulated by taking into account both the lower and upper class limit value for the fertilizer-P recovery fraction, for any given P retention class, during the crop yield modelling component of the present project.

Table 2

Indicative recovery fraction of phosphorus from broadcast superphosphate by soil P retention class.

P retention potential[a]	Recovery fraction[bd] (kg kg^{-1})	Broad soil type
Very High	0.02	Volcanic soils, rich in allophane (Andosols)
	.	Strongly acid, oxidised pyritic material (Thionic Fluvisols)
	.	Very acid, 'podsolised' soil material (if there is a thick spodic B horizon at shallow depth)
	.	Old, very acid red or yellow soil material, rich in iron or aluminum (Ferralsols; ferric and plinthic Acrisols)
High	0.05[c]	Acid, red clayey soils, rich in iron or aluminum (incl. Acrisol and Nitosols units; clayey, ferralic soil units)
Moderate	0.10	Alkaline, calcareous soils
	.	Swelling-cracking clay soils (2:1 clays)
	.	Weakly to medium acid, well-structured clay
	.	Near neutral, (strongly) humic soil material
	0.15	Young near-neutral alluvial clay
Low	.	Young, neutral, coarse and medium textured alluvial material
	.	Organic soil material (Histosols)
	0.30	Quartzitic sands (Arenosols)

[a] Classes for P retention potential as derived from the present study; within a given P retention class, the actual recovery fraction will be determined by climate, crop selection, land management practices, soil type, and P fertilizer (type) application history.

[b] Figures are for broadcast application of superphosphate for a default, rainfed cereal crop and defined by kg P in harvested yield per kg P applied for broad soil types (adapted from Driessen and Konijn, 1992); recovery fraction in year of application of fertilizer. The correspondence between a P retention potential class and range in P recovery fraction should be seen as a first approximation; values should be refined when more detailed information, derived from field experiments for specified crops and agro-ecological zones, becomes available.

[c] Tentative class boundary based on other sources (AgSource, 2006).

[d] For the long-term P recovery fraction, say over a 5-year period, the class limits could be multiplied by two, except for Andosols and strongly calcareous soils, as a coarse approximation based on generalized data presented by Smil (2000).

Limited availability to plants of phosphorus in soils may be due to deficiency and/or severe P retention (this study). Soil P deficiency may be due to the low P-status of the parent material, intensity and duration of weathering, prolonged anthropogenic mismanagement through imbalance between nutrient inputs and outputs, and losses of P by erosion and surface run-off (e.g., Stoorvogel *et al.*, 1993; Fairhurst *et al.*, 1999; Gichuru *et al.*, 2003; Lesschen *et al.*, 2007). In many areas of the world, regular application of P containing fertilizers will be necessary to increase and sustain crop yields; nutrient interactions (e.g., NPK) should be considered explicitly in this process.

Relatively little is known about the effects of organic materials on P-solubilisation and sorption-desorption processes when such materials are applied along with inorganic fertilizers (Palm *et al.*, 1997). Improved N and P status and overall soil fertility can result in concomitant improvements of soil organic matter and water holding properties. As such, judicious management of soil fertility can also play an important role in soil carbon sequestration to mitigate increasing global atmospheric CO_2 concentration, but the possible net gains are finite (e.g., Janzen, 2006; Lal, 2009; Powlson *et al.*, 2011)

5 Conclusions

Geographical and attribute data held in the ISRIC-WISE database were analysed to map the P retention potential of major world soils. Seen the complexity of P sorption/mobilization processes in the soil, broad assumptions were used to define four different classes for soil P retention potential; main differentiating criteria are soil pH, inferred soil mineralogy, and clay content. The corresponding class boundaries are fuzzy, not crisp; similarly, the derived values for soil pH, clay content, and CEC_{clay} have large uncertainties attached to them. The present world map of soil P retention potential and underpinning tabular data should be seen as a first approximation (i.e., exploratory map), pending the availability of more detailed knowledge at the regional level (scale <1:5 million).

Limited availability of P in soils to crops may be due to deficiency and/or severe P retention. The class for P retention potential for a given soil unit, respectively mapping unit, can be coupled to recovery rates for fertilizer P derived from the literature. In combination with auxiliary knowledge/databases on climate, input levels, P-fertilizer application history, and crop-specific soil requirements, this information can serve as input to crop production models. As such, results of this study should permit spatially more detailed, integrated model-based studies of environmental sustainability and agricultural production. Within the current project on 'Resource scarcity and distribution in a changing world,' the initial focus will be on model applications for Africa, but applied tools are principally developed for global usage. Global modelers may also use the data for broad scale analyses.

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Appendix I Structure of output table

(see table *P_RetMap_FINAL* in database *ISRIC_Phosphorus_Retention_Potential.mdb*)

Name	Type	Description
SUID	Integer	Unique ID for map unit (note: corresponds with SNUM on the Digtal Soil Map of the World, FAO, 1995)
MainCLASS	Text	Dominant soil P retention potential class in map unit, given as leftmost three characters of *FullCLASS*, e.g. 'Mo2', see text for details)
FullCLASS	Text	Full code for soil P retention potential, sorted according to most limiting class in map unit (*FullCLASS* is the alias for *Code_sorted_converted*), for example 'Mo2Lo3VH4Hi4'. Each *FullCLASS* may consist of a wide range of different soil mapping units; see Appendix III for an example
VH	Integer	Proportion of map unit with a Very High P retention potential
Hi	Integer	Proportion of map unit with a High P retention potential
Mo	Integer	Proportion of map unit with a Moderate P retention potential
Lo	Integer	Proportion of map unit with a Low P retention potential
MISC	Integer	Proportion of map unit consisting of miscellaneous units (i.e., WR (water), GL (glaciers), RK (rock outcrops))
___	Text	Separator
FAOSOIL	Text	Map unit code from Digital Soil Map of the World (FAO, 1995)
SoilMapUnit	Text	Map unit composition code, as used for WISE (see Batjes, 2006)
SOIL1[a]	Text	Dominant FAO (1974) soil unit in map unit (or grid cell)
PROP1	Integer	Proportion of SOIL1 in map unit
SOIL2	Text	Next, dominant FAO soil unit in map unit (or grid cell)
PROP2	Integer	Proportion of SOIL2 in map unit
SOIL3	Text	As above for SOIL3 (when applicable)
PROP3	Integer	As above for SOIL3 (when applicable)
SOIL4	Text	As above for SOIL4 (when applicable)
PROP4	Integer	As above for SOIL4 (when applicable)
SOIL5	Text	As above for SOIL5 (when applicable)
PROP5	Integer	As above for SOIL5 (when applicable)
SOIL6	Text	As above for SOIL6 (when applicable)
PROP6	Integer	As above for SOIL6 (when applicable)
SOIL7	Text	As above for SOIL7 (when applicable)
PROP7	Integer	As above for SOIL7 (when applicable)
SOIL8	Text	As above for SOIL8 (when applicable)
PROP8	Integer	As above for SOIL8 (when applicable)
SOIL9	Text	As above for SOIL9 (when applicable)
PROP9	Integer	As above for SOIL9 (when applicable)
SOIL10	Text	As above for SOIL10 (when applicable)
PROP10	Integer	As above for SOIL10 (when applicable)

[a] The number of soil units can range from 1 to 8 depending on the map unit composition.

Appendix II Estimated P retention potential by FAO soil unit

FAO74	FAO74_name	pH water[a]	Sand	Silt	Clay	CEC_{clay}	Classification	P retention
A	Acrisols	5.0	46.4	19.8	33.8	14		High
Af	Ferric Acrisol	5.1	46.8	18.2	35.0	12		Very High
Ag	Gleyic Acrisol	5.0	43.2	27.0	29.8	23		High
Ah	Humic Acrisol	5.0	34.8	22.2	43.0	14		High
Ao	Orthic Acrisol	5.0	51.4	18.6	30.0	15		High
Ap	Plinthic Acrisol	4.8	43.6	23.2	33.2	12		Very High
B	Cambisols	6.3	40.4	30.2	29.4	40		Low
Bc	Chromic Cambisol	6.9	38.2	27.6	34.2	36	X	Moderate
Bd	Dystric Cambisol	5.1	44.8	31.2	24.0	31	X	Moderate
Be	Eutric Cambisol	6.9	42.4	31.0	26.6	52		Low
Bf	Ferralic Cambisol	5.0	43.4	21.8	34.8	12	(X)	High
Bg	Gleyic Cambisol	6.3	38.8	29.8	31.4	37		Low
Bh	Humic Cambisol	5.2	44.8	27.0	28.2	38	(X)	High
Bk	Calcic Cambisol	8.2	34.4	38.4	27.2	56		Moderate
Bv	Vertic Cambisol	7.2	26.2	27.0	46.8	60		Moderate
Bx	Gelic Cambisol	5.3	38.0	40.0	22.0	40	X	Moderate
C	Chernozems	7.6	26.2	43.0	30.8	64		Moderate
Cg	Glossic Chernozem	7.6	26.2	43.0	30.8	64		Moderate
Ch	Haplic Chernozem	7.4	23.6	47.4	29.0	70		Moderate
Ck	Calcic Chernozem	8.0	25.6	42.4	32.0	58		Moderate
Cl	Luvic Chernozem	7.4	30.0	36.8	33.2	59		Moderate
D	Podzoluvisols	5.2	51.8	35.6	12.6	52	x	Moderate
Dd	Dystric Podzoluvisol	5.1	33.6	47.2	19.2	66	x	Moderate
De	Eutric Podzoluvisol	5.3	57.2	32.4	10.4	52	X	Moderate
Dg	Gleyic Podzoluvisol	5.2	38.8	43.2	18.0	47	X	Moderate
Ex	Rendzinas	7.3	44.0	32.5	23.5	63		Moderate
F	Ferralsols	5.0	38.0	15.2	46.8	7		Very High
Fa	Acric Ferralsol	5.0	26.0	18.4	55.6	3		Very High
Fh	Humic Ferralsol	5.0	30.0	17.6	52.4	6		Very High
Fo	Orthic Ferralsol	5.0	40.2	16.2	43.6	7		Very High
Fp	Plinthic Ferralsol	5.1	40.4	14.4	45.2	7		Very High
Fr	Rhodic Ferralsol	5.3	31.6	15.8	52.6	9		Very High
Fx	Xanthic Ferralsol	4.7	47.8	11.2	41.0	5		Very High
G	Gleysols	5.9	37.2	29.6	33.2	35		Moderate
Gc	Calcaric Gleysol	7.8	41.8	26.2	32.0	40		Moderate
Gd	Dystric Gleysol	5.0	37.4	27.4	35.2	28	X	Moderate
Ge	Eutric Gleysol	6.3	35.2	30.8	34.0	39		Low
Gh	Humic Gleysol	5.3	42.4	28.6	29.0	32		High
GL	Glaciers/Land Ice	-2.0	-2.0	-2.0	-2.0	-1		Glaciers
Gm	Mollic Gleysol	6.7	36.0	28.6	35.4	41		Low
Gp	Plinthic Gleysol	5.2	41.0	27.6	31.4	15	X	High
Gx	Gelic Gleysol	6.6	30.4	46.0	23.6	68	X	Low
H	Phaeozems	6.8	32.2	34.0	33.8	58		Low
Hc	Calcaric Phaeozem	8.1	28.8	41.0	30.2	65		Moderate

FAO74	FAO74_name	pH water[a]	Sand	Silt	Clay	CEC$_{clay}$	Classification	P retention
Hg	Gleyic Phaeozem	6.5	31.0	34.0	35.0	53	X	Low
Hh	Haplic Phaeozem	6.7	36.8	32.8	30.4	58		Low
Hl	Luvic Phaeozem	6.6	29.4	33.6	37.0	59		Low
Ix	Lithosols	7.5	48.0	29.0	23.0	42		Moderate
J	Fluvisols	7.4	43.0	32.6	24.4	45		Moderate
Jc	Calcaric Fluvisol	8.1	42.6	37.8	19.6	74		Moderate
Jd	Dystric Fluvisol	5.0	52.8	25.2	22.0	24		Moderate
Je	Eutric Fluvisol	7.1	43.8	31.8	24.4	52		Moderate
Jt	Thionic Fluvisol	3.9	21.4	33.4	45.2	26	X	Very High
K	Kastanozems	7.9	29.8	39.2	31.0	66		Moderate
Kh	Haplic Kastanozem	7.7	29.0	40.8	30.2	85		Moderate
Kk	Calcic Kastanozem	8.2	30.0	38.8	31.2	54		Moderate
Kl	Luvic Kastanozem	7.7	30.4	38.4	31.2	66		Moderate
L	Luvisols	6.3	49.4	21.8	28.8	34		Low
La	Albic Luvisol	6.4	54.0	26.2	19.8	51		Low
Lc	Chromic Luvisol	6.4	43.2	23.4	33.4	36	X	Moderate
Lf	Ferric Luvisol	6.1	58.4	13.8	27.8	20	X	Moderate
Lg	Gleyic Luvisol	6.4	44.0	26.0	30.0	43		Low
Lk	Calcic Luvisol	8.1	53.0	22.6	24.4	51		Moderate
Lo	Orthic Luvisol	6.2	47.6	25.0	27.4	38		Low
Lp	Plinthic Luvisol	6.1	54.2	20.2	25.6	24	X	Moderate
Lv	Vertic Luvisol	7.0	28.2	24.0	47.8	53		Moderate
Mg	Gleyic Greyzem	6.5	22.8	50.4	26.8	63		Low
Mo	Orthic Greyzem	6.7	23.0	49.4	27.6	64		Low
N	Nitosols	5.5	34.4	19.6	46.0	20	X	High
Nd	Dystric Nitosol	5.3	33.4	19.8	46.8	15		High
Ne	Eutric Nitosol	6.1	45.4	17.0	37.6	25	X	Moderate
Nh	Humic Nitosol	5.4	18.4	22.6	59.0	27		High
O	Histosols	5.0	34.4	33.2	32.4	-3	X	Low
Od	Dystric Histosol	4.5	33.0	32.4	34.6	-3	X	Low
Oe	Eutric Histosol	5.8	36.0	32.6	31.4	-3	X	Low
Ox	Gelic Histosol	5.1	34.4	33.2	32.4	-3	X	Low
P	Podzols	4.7	80.2	14.8	5.0	65	X	Moderate
Pg	Gleyic Podzol	4.8	81.2	14.0	4.8	67	X	Moderate
Ph	Humic Podzol	4.6	88.8	7.4	3.8	48	X	Moderate
Pl	Leptic Podzol	4.9	68.6	23.4	8.0	60	X	Moderate
Po	Orthic Podzol	4.8	79.8	15.2	5.0	75	X	Moderate
Pp	Placic Podzol	4.9	64.8	26.6	8.6	66	X	Moderate
Q	Arenosols	5.8	88.4	5.6	6.0	37		Low
Qa	Albic Arenosol	5.4	87.0	8.8	4.2	37		Low
Qc	Cambic Arenosol	6.3	88.8	6.0	5.2	43		Low
Qc[c]	Dunes/Shifting sands	6.3	98.0	1.0	1.0	43		Low
Qf	Ferralic Arenosol	5.4	88.4	5.0	6.6	25		Low
Ql	Luvic Arenosol	5.6	88.0	5.0	7.0	38		Low
R	Regosols	6.8	62.6	22.4	15.0	42		Low
Rc	Calcaric Regosol	8.1	49.8	30.4	19.8	51		Moderate
Rd	Dystric Regosol	5.1	64.8	21.4	13.8	24		Moderate
Re	Eutric Regosol	6.8	66.6	19.8	13.6	53		Low
RK	Rock outcrops	-7.0	-7.0	-7.0	-7.0	-1		Rocks
Rx	Gelic Regosol	6.3	49.6	34.0	16.4	37		Low
S	Solonetz	8.2	39.2	30.6	30.2	55		Moderate
Sg	Gleyic Solonetz	8.0	35.8	33.0	31.2	53		Moderate
Sm	Mollic Solonetz	8.2	27.6	42.4	30.0	80		Moderate

FAO74	FAO74_name	pH water[a]	Sand	Silt	Clay	CEC_{clay}	Classification	P retention
So	Orthic Solonetz	8.2	43.6	26.6	29.8	55		Moderate
T	Andosols	5.9	42.4	37.6	20.0	81	X	Very High
Th	Humic Andosol	5.7	39.0	41.2	19.8	83	X	Very High
Tm	Mollic Andosol	6.4	41.4	35.0	23.6	62	X	Very High
To	Ochric Andosol	6.2	30.2	40.4	29.4	80	X	Very High
Tv	Vitric Andosol	6.0	63.8	27.0	9.2	146	X	Very High
Ux	Rankers	5.0	55.5	24.0	20.5	17		Moderate
V	Vertisols	7.6	19.8	24.8	55.4	70		Moderate
Vc	Chromic Vertisol	8.0	16.8	28.4	54.8	72		Moderate
Vp	Pellic Vertisol	7.3	21.8	22.8	55.4	70		Moderate
W	Planosols	6.1	44.6	25.8	29.6	40	X	Low
Wd	Dystric Planosol	4.8	45.6	25.0	29.4	22	X	Moderate
We	Eutric Planosol	6.1	46.6	24.2	29.2	41	X	Low
Wh	Humic Planosol	6.1	41.8	31.4	26.8	40	X	Low
Wm	Mollic Planosol	6.8	20.6	43.8	35.6	55	X	Low
WR	Water/Oceans	-1.0	-1.0	-1.0	-1.0	-1		Water
Ws	Solodic Planosol	6.9	53.2	18.6	28.2	38	X	Low
X	Xerosols	8.0	51.4	25.4	23.2	50		Moderate
Xh	Haplic Xerosol	8.1	43.0	31.8	25.2	44		Moderate
Xk	Calcic Xerosol	8.3	39.8	36.4	23.8	73		Moderate
Xl	Luvic Xerosol	7.6	64.4	13.8	21.8	50		Moderate
Xy	Gypsic Xerosol	8.0	34.6	42.0	23.4	30		Moderate
Y	Yermosols	8.1	47.4	31.0	21.6	44		Moderate
Yh	Haplic Yermosol	8.3	52.0	30.8	17.2	47		Moderate
Yk	Calcic Yermosol	8.2	41.0	36.6	22.4	45		Moderate
Yl	Luvic Yermosol	8.0	56.8	20.8	22.4	43		Moderate
Yt	Takyric Yermosol	8.1	47.4	31.0	21.6	44		Moderate
Yy	Gypsic Yermosol	7.8	42.4	35.0	22.6	43		Moderate
Z	Solonchaks	8.1	39.0	31.2	29.8	48		Moderate
Zg	Gleyic Solonchak	8.4	36.4	31.6	32.0	45		Moderate
Zm	Mollic Solonchak	8.1	30.8	28.8	40.4	53		Moderate
Zo	Orthic Solonchak	8.1	41.4	30.8	27.8	50		Moderate
Zt	Takyric Solonchak	8.1	39.0	31.2	29.8	48		Moderate

[a] Parameter estimates for soil pH, clay content and CEC_{clay} are depth-weighted values, see text. The derived ratings for P retention potential should be seen as a first approximation. They may be used in GIS-based studies at continental and broader scales (<1:5 million), provided the associated uncertainties are duly understood.

[b] Soil units are useful carriers of soil information; qualitative information on soil mineralogy embedded in the soil unit name (e.g., chromic, ferralic, ferric, plinthic, humic or histic) has been used as a criterion for rating soil phosphorus retention potential for several soil units (see text; flagged with 'X' in the above Table). For example, CEC_{clay} does not suffice as a proxy for soil mineralogy to identify Andosols or Histosols.

[c] Mapping units 'WD36' and 'WD3043' are comprised of dunes and shifting sand; this miscellaneous unit is coded 'D/SS' unit on the Digital Soil Map of the World (FAO, 1995). The sand content of these miscellaneous units has been set at 98%, while other soil properties were assumed to be similar to those of cambic Arenosols (see Batjes, 2006).

Appendix III Mapping units included in soil P retention potential class 'Mo1Hi4 with 90% Mo and 90% Hi-rated soil units'

SUID	FullClass	FullCLASS	VH	Hi	Mo	Lo	MISC	FAOSOIL	SoilMapUnit
11	Mo1	Mo1Hi4	0	10	90	0	0	Bd31-2c	Bd1Bh5 [WD11]
229	Mo1	Mo1Hi4	0	10	90	0	0	Rd2-2c	Rd3Ix4Bh5Jd5 [WD229]
446	Mo1	Mo1Hi4	0	10	90	0	0	Bc18-c	Bc3Ix4Rd4Ao5 [WD446]
715	Mo1	Mo1Hi4	0	10	90	0	0	Lc54-2/3a	Lc1Nd5 [WD715]
762	Mo1	Mo1Hi4	0	10	90	0	0	Lf77-1/2a	Lf1Gp5Vp5 [WD762]
827	Mo1	Mo1Hi4	0	10	90	0	0	Ne34-3c	Ne1Nh5 [WD827]
840	Mo1	Mo1Hi4	0	10	90	0	0	Ne44-2/3ab	Ne1Gh5Ix5 [WD840]
932	Mo1	Mo1Hi4	0	10	90	0	0	Rd20-2c	Rd2Ix4Nd5 [WD932]
1924	Mo1	Mo1Hi4	0	10	90	0	0	Lf85-2ab	Lf3Lc4Ne4Ao5 [WD1924]
3053	Mo1	Mo1Hi4	0	10	90	0	0	Dg2-1ab	Dg2Gd4Gh5 [WD3053]
3054	Mo1	Mo1Hi4	0	10	90	0	0	Dg2-1ab	Dg2Gd4Gh5 [WD3054]
3235	Mo1	Mo1Hi4	0	10	90	0	0	Ph9-1ab	Ph1Gd5Gh5 [WD3235]
3784	Mo1	Mo1Hi4	0	10	90	0	0	Lc97-3b	Lc1Gh5Je5 [WD3784]
3830	Mo1	Mo1Hi4	0	10	90	0	0	Ne58-1bc	Ne3Bc4Lf4Ao5 [WD3830]
3846	Mo1	Mo1Hi4	0	10	90	0	0	Rd25-1a	Rd2Jd4Nd5 [WD3846]
3930	Mo1	Mo1Hi4	0	10	90	0	0	De6-2ab	De3Dg4Gd4Gh5 [WD3930]
3931	Mo1	Mo1Hi4	0	10	90	0	0	De6-2b	De3Dg4Gd4Gh5 [WD3931]
3932	Mo1	Mo1Hi4	0	10	90	0	0	De7-2ab	De2Gd4Gh5 [WD3932]
3933	Mo1	Mo1Hi4	0	10	90	0	0	De7-2b	De2Gd4Gh5 [WD3933]
3936	Mo1	Mo1Hi4	0	10	90	0	0	Dg2-2ab	Dg2Gd4Gh5 [WD3936]
3937	Mo1	Mo1Hi4	0	10	90	0	0	Dg2-2b	Dg2Gd4Gh5 [WD3937]
4031	Mo1	Mo1Hi4	0	10	90	0	0	Ph9-1ab	Ph1Gd5Gh5 [WD4031]
4186	Mo1	Mo1Hi4	0	10	90	0	0	De7-2ab	De2Gd4Gh5 [WD4186]
4515	Mo1	Mo1Hi4	0	10	90	0	0	Jd10-2/3a	Jd3Bd4Gh5Rd5 [WD4515]
4765	Mo1	Mo1Hi4	0	10	90	0	0	Je24-2a	Je2Lc4Gh5 [WD4765]
5919	Mo1	Mo1Hi4	0	10	90	0	0	Kh28-2b	Kh1Nd5 [WD5919]
6359	Mo1	Mo1Hi4	0	10	90	0	0	Bd51-2abc	Bd2Bh5Ix5Pp5 [WD6359]
6421	Mo1	Mo1Hi4	0	10	90	0	0	Bd75-2ab	Bd3Gd4Gh5Pl5 [WD6421]
6670	Mo1	Mo1Hi4	0	10	90	0	0	Ne58-1bc	Ne3Bc4Lf4Ao5 [WD6670]

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[a] For details and abbreviations see Appendix I.

[b] Codes for the SoilMapUnit have the following format: 'Ah2Ao4Vc4'. The relative extent of each soil unit (e.g., Ah for humic Acrisols) has been expressed in 5 classes to arrive at a compact map unit code: 1 - from 80 to 100 per cent; 2 - from 60 to 80 per cent; 3 - from 40 to 60 per cent; 4 - from 20 to 40 per cent, and 5 - less than 20 per cent (see Batjes, 2006).

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